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Energy efficiency of waste-to-energy plants with a focus on the comparison and the constraints of the 3T method and the R1 formula

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A B S T R A C T

Managing the municipal solid waste (MSW) is a task that requires the combination of multiple strategies in order to follow the concept of circular economy. Waste-to-Energy (WtE) plants are producing electricity and heat but also have other byproducts that need to be disposed or can be reused. The standard method for assessing the WtE plants is the utilization of the R1 formula. The R1 formula has several limitations and is not able to integrate more parameters like the recovery of metals. The integration of the climate correction factor can improve the R1 up to 1.25 times but this factor is related to the Heating Degree Days, which is a rapidly declining value due to climate change. Contrary to the R1 Formula, the 3T Method is a novel method that can take into consideration all the range of products like syngas and biooil in a thermodynamically consistent way. These two methods were used to analyze three characteristic incineration plants and two gasification plants and this is the first time that this comparison is being presented. The results showed that the two methods have different ranges of returned values, with the R1 returning values (usually) between 0.5 and 1.1 and the 3T method returning values between 0.2 and 0.3. The 3T method on the one hand promotes high electrical efficiencies, i.e. 3T values approach the 0.3 mark for 30% electrical efficiency, and on the other hand promotes polygeneration where the recovery of char and metals can elevate the 3T value well above the 0.3 level for only 15% electrical efficiency and 70% metal recovery.

1. Introduction

Municipal solid waste (MSW) primarily consist from everyday items –that are usually not toxic or poisonous-which are casually disposed by households [1]. This stream (of waste generation) is a peculiar one since it is created on a very disperse manner, i.e. moderate amounts of waste are generated from individual households that can be separated with denotable distances [2]. Thus, the management of municipal solid waste has been implemented with a combination of tools and strategies rather than the application of a single method. The Waste Framework Directive 2008/98/EU [3] provided the concept of the inverted pyramid where a set of strategies where prioritized in accordance to the cascade principle and the concept of sustainability and circular economy. The principal concept is that these guidelines aim to reduce the generation of waste and extend their life cycle. Therefore, the reduction, the reuse and the recycling of waste are being promoted as primary options. In case that the application of the three Rs (reducing-reusing-recycling) is not possible, the preference is to aim for the energy recovery from waste before finally pursuing the option of discarding the MSW in disposal facility, i.e. mainly sanitary landfills. These sustainable management strategies are not being applied only in European Union but in other regions as well. The Environmental Protection Agency of the United State (EPA) applies a very similar "waste management hierarchy system" for the case of managing non-hazardous waste [4]. This hierarchical system, which has been introduced and applied by European Union and the United States, is becoming the "way-to-go" in the field of municipal solid waste management and is being integrated in several other countries as well [5]. Perrot and Subiantoro (2018) provided an extensive critical review about the case of New Zealand, which implements the same waste management strategies and focuses as well on the three Rs (reducing-reusing-recycling) [6]. The authors also discussed the role of energy recovery (defined as waste-to-energy) technologies and assessed their costs and their environmental pollution potential.

Waste-to-energy (WtE) primarily refers to the thermal processing of municipal solid waste for the recovery of energy and materials. Nonetheless, it is common that other energy recovery technologies are lumped together as well under this "umbrella-term", like the study of

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Nomenclature

β	chemical exergy factor
B, B_{ph}, B_{ch}	exergy, physical exergy, chemical exergy (MJ)
CCF	Climate Correction Factor
Ep	annual energy produced as heat or electricity
Ef	annual energy input to the system from fuels contributing to the production of steam (GJ/year)
Ew	annual energy contained in the treated waste calculated using the net calorific value of the waste (GJ/year)
Ei	annual energy imported excluding Ew and Ef (GJ/Year)
HDD	Heating Degree Days
LHV	lower heating value (MJ/kg)
ηel	net electric efficiency
ηth	net thermal efficiency
Pel	electric power
Paux	electric self-consumption of the auxiliary equipment
Pth	thermal power
S, s	entropy, specific entropy (J K-1, J K-1 kg-1)
T, T0	temperature, temperature of environment (K)
$\Phi waste_e$	(waste) mass flow rate (kg/s)

New Zealand that was mentioned before [6]. The British Department for Environment, Food & Rural Affairs (DEFRA) has been using the term "Energy-from-Waste" which is a more suitable terminology that can include all the energy recovery technologies from municipal solid waste [7]. Tong et al. (2018) is utilizing the phrase "energy recovery from waste" but also defines all these technologies as "WtE practices" [8]. Beegle & Borole (2018) have used a similar approach [9] and this denotes that it is becoming widely acceptable that the term "WtE" can also be used for non-thermal technologies. However, it should be stated that the primer WtE technology is incineration [10]. The application of WtE as a waste management strategy has several advantages that make the energy recovery actions appealing and adjustable to different waste management schemes. By means of thermal and non-thermal treatments, the volume of MSW are reduced significantly and the waste (usually) become inert or safe to dispose. Additionally, these technologies have the aim of producing electricity, heat and reusable materials (e.g. metals, bottom ash), which highlights the important role that WtE can have in the new framework of circular economy [11]. The aspect of circular economy is becoming increasingly significant since it supported by new legislation frameworks, like the one from European Union [12].

The proper analysis and characterization of WtE technologies is an issue of high interest and importance since it is a widely applied technology worldwide. According to the Confederation of WtE Plants [13], 510 WtE plants were operating in Europe during the year 2016, with a total annual processing ability that reached approximately 80 million tons of municipal solid waste. In European Union, it is common to have WtE plants in close proximity to the city centers in order to valorize the produced heat. WtE plants supply heat in high percentages to several European urban district heating networks, e.g. 50% in Paris, 60% in Malmö, 75% in Brescia and 30% in the Greater Copenhagen area. Zhang et al. (2015) presented the rapid growth of the Chinese WtE industry (incineration plants) which by the year 2013 represented the 30% of the total waste management volume with 166 plants [14]. This growth has been reported to accelerate even further and is projected that the total number of plants will exceed 500 within the next few years [10]. This success of WtE plants and their integration has raised the interest for WtE technologies in countries that –until now-have moderate or none WtE applications like the cases of Ecuador [15] and Serbia [16].

As mentioned in the previous paragraph, WtE technologies contribute on several different levels of the waste management hierarchy. On the one hand, the scope is energy recovery for the production of electricity and heat. On the other hand, WtE plants are disposing facilities since their final solid residue is disposed in landfills. European legislation addressed this problem in the Waste Framework Directive of 2008, where WtE plants were separated in recovery and disposal operations in accordance to the parameters that were introduced in annexes 1 and 2 of the document [17]. Several studies and legislative efforts have tried to address the categorization of WtE plants and to improve the conventional assessment techniques. Beegle and Borole, 2018 used energy efficiency and economic factors and thus were able to assess the economic benefits of different technologies [9] along with their performance. Astrup et al., 2015 presented a thorough and comprehensive review of studies that used LCA analysis for the assessment of WtE technologies. The authors identified several methodological errors and inconsistencies in many studies and questioned the calculation principles that were used in many cases [18]. Although this criticism is not aiming to diminish the importance of LCA it should be stated that several steps should be made towards consistency and transparency. Finally, several studies focus on the decision-making between different energy recovery strategies, e.g. incineration vs anaerobic digestion, but very few provide the framework for the direct comparison between dfferent WtE technologies [19]. Several methodologies have been proposed in order to characterize their operation like the classification system of the US Environmental Protection Agency or the Envelopment Analysis method [20]. Although these methods can be effective, a critical question to be made is how the performance of the WtE plants should be assessed in order to have solid quantifiable results.

A big contribution of the Waste Framework Directive 2008/98/EU [3] was the introduction of the quasi-thermodynamic equation that is commonly referred to as the R1 formula. This has been a first and (very) significant step for the numerical assessment of WtE plants. Since then, the R1 formula has evolved to become more a "utilization efficiency" formula rather than a pure energy efficiency formula. This has been done by introducing also a factor that is usually referred to as "the climate correction factor" (Directive 2015/1127/EU) that aims to account for the demand (or not) for heat in accordance to the local climate conditions [21]. This development is not necessarily bad or wrong, but it totally changes the scope of the original intent, which was to assess objectively the efficiency of a given technology. Beyond this argument, the drawbacks of the R1 formula have been identified to be (mainly) two. Firstly, the R1 formula is designed to be applied exclusively to conventional incineration facilities [17], and has no room for integrating other thermal technologies, e.g. gasification and pyrolysis, let alone non-thermal technologies like the case of anaerobic digestion. Secondly, WtE plants are recycling the metals, which is an important side-operation that should be taken into consideration.

Vakalis et al., 2018 [22] introduced a new methodology with the name "3T Method", which assesses WtE plants in an integrated way. Along with conventional Combined Heat and Power (CHP) efficiency, the 3T method accounts as well for the quality of the products, whether it is the exergy of produced heat, the exergy efficiency of the products (e.g. char, biooil) or the exergy efficiency of the metals. A critical gap in the literature is the lack of comparison between the R1 formula and the 3T method in order to calculate the range of numerical results and assess the constraints of each methodology. This numerical comparison between the two methods and the critically comparison of the results is the scope of this study. Section 2 will provide the basic framework of the two methodologies and Section 3 will present the results and will critically discuss the two methodologies.

2. Materials and methods

In the framework of this study, the R1 formula and the 3T method will be assessed for their efficiency assessment of WtE plants. These two methods are presented only briefly below, since the introduction of these two methods has been done in previous publications and the meaning of their development surpasses the scope of this manuscript.

The formula is defined in equation (1) as follows:

$$R1 = \frac{(Ep - Ef–Ei)}{0.97 * (Ew + Ef)} \quad (1)$$

The main point if using the R1 formula was to separate the recovery operators, i.e. energy producers, from the disposal operators who could be also identified as waste destroyers. Older facilities need to have R1 values higher than 0.6 and for newer facilities the requirement rises to a value of 0.65. In the framework of this study, the climate correction factor will be presented as well and its effect on the R1 formula will be discussed. In principle, the locations that have more than 3350 heating degree-days receive no bonus because the heat demand is very high. Thus, the climate correction factor is set to 1. On the other side, locations with less than 2150 heating degree days receive the full bonus because the heat demand is very low and the climate correction factor is set to 1.25. The locations that have "in-between" values of heating degree days get assigned a climate correction factor that is calculated from equations (2) and (3), for old and new plants respectively.

$$\text{Old plants} = (0{,}25/1\,200) \times \text{HDD} + 1{,}698 \quad (2)$$

$$\text{New plants} = -(0{,}12/1\,200) \times \text{HDD} + 1{,}335 \quad (3)$$

On the other hand, Vakalis et al. (2018) [22] took into consideration the parameters that were mentioned in the latter part of the "Introduction" section and were related to the standard efficiency and the quality of the products. Characteristically, the standard CHP was used as it is defined in equations (4) and (5) for electrical and thermal efficiency respectively. Exergy relates to the maximum attainable work in the occurrence of reversible equilibrium between a system and its surroundings [23]. The general exergy equation is presented in equation (6) and the special case of chemical exergy in equation (7). The chemical exergy calculation is being performed by means of correlating the chemical exergy value with the lower heating value. This correlation factor is commonly known as Szargut β factor and is dependent on the elemental composition of a specific compound [23]. For the case of municipal solid waste management, this is a rather complicated task since the composition of the waste mixture may fluctuate significantly even in short time intervals. At the same time, some waste fractions may be very diverse, like plastics, metals and biogenic wastes. In these case the exergy of a fraction should be further compartmentalized in respect to the specific elemental characteristics of each sub-fraction.

$$\eta_{el} = (P_{el} - P_{aux})/(\Phi_{waste} \times LHV_{waste}) \quad (4)$$

$$\eta_{th} = (P_{th})/(\Phi_{waste} \times LHV_{waste}) \quad (5)$$

$$B = h - h_0 - T_0(s - s_0) \quad (6)$$

$$B_{ch} = \beta \times LHV \quad (7)$$

The individual efficiencies for the electricity, the heat and the recovered metal are plotted in a radar graph and the area of the triangle is calculated as shown in Fig. 1. On the top half, Fig. 1 presents the specialized solution for incineration plants since this will be the focus of this study. For the case of technologies with more output streams, the more complicated trapezoid solution should be applied which can be seen in the combined upper and lower parts of the Figure.

As mentioned also by several publications that are used in the framework of this study, i.e. [10,18], the most representative WtE technology is incineration. Thus, as starting point, the two methods will be used for the evaluation of three representative incineration plants that were used in a previous publication [22] and two representative gasification plants that were presented in another published study [23]. The parameters that were used for the analysis are presented in Table 1.

3. Results and discussion

3.1. Comparative results between the 3T method and the R1 formula

Fig. 2 shows the application of the R1 formula and the 3T method on the three representative incineration plants and the two representative gasification plants of Table 1. The 3T values for the incineration plants A, B & C are 0.217, 0.206 and 0.246 respectively. Gasification plant D had a 3T value of 0.213, and for plant E the value was 0.205. Vakalis et al. (2018), initially presented the results for the 3T Method applied on plants A, B & C [22] and the initial basic scope of this work was dual. Expand the application of the 3T method on gasification plants and present the analysis for the application of the R1 formula for plants A-E. As shown in Fig. 2, the R1 values for plants A, B & C are 1.07, 1.073 and 1.23 respectively, which shows that plants with

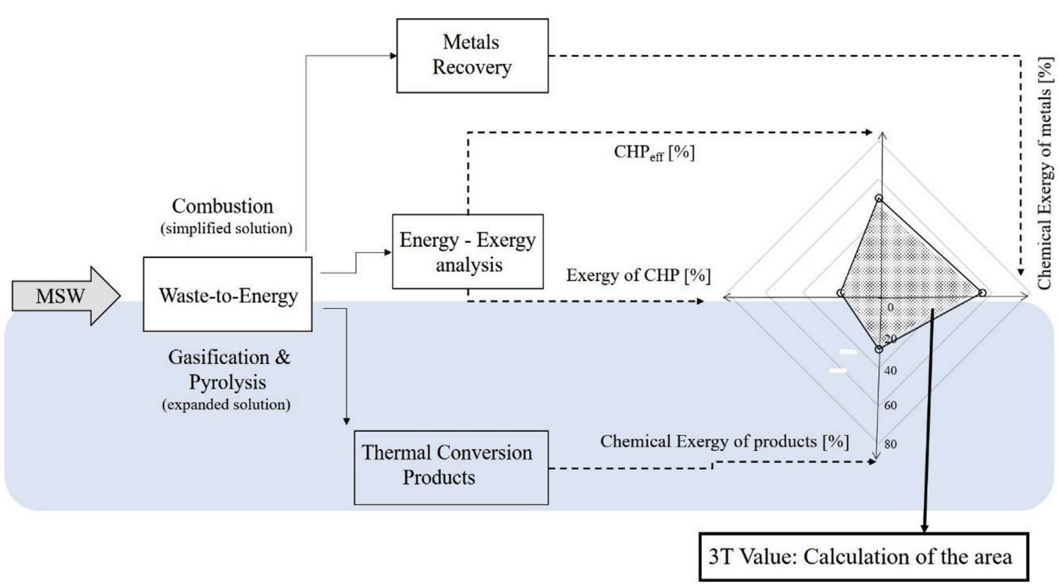

Fig. 1. 3T solutions for different WtE scenarios.

Table 1
Parameters of representative plants for the calculation of R1 formula & 3T method (Sources: [22,23].).

	Plant A	Plant B	Plant C	Plant D	Plant E
Electrical efficiency [%]	17	21	27	18.3	16.8
Thermal efficiency [%]	55	45	45	49.9	52.5
Temperature of output heat [°C]	85	85	85	90	70
Exergy efficiency [%]	25.22	27.46	33.23	25.8	22.8
Exergy efficiency of metals [%]	35	35	35	35	35
Exergy of products (char) [%]	–	–	–	2	1.7

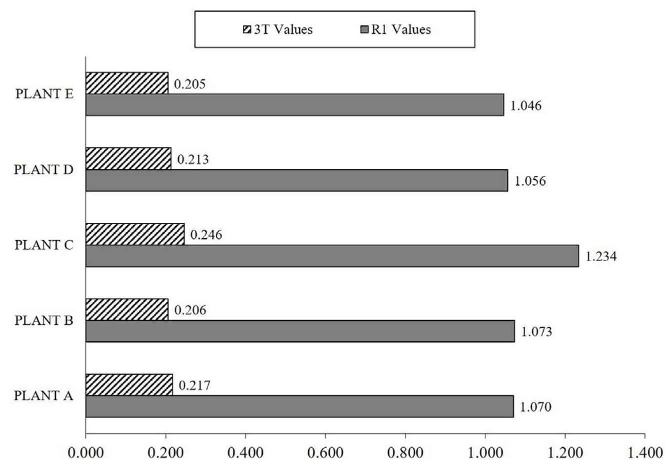

Fig. 2. Application of the R1 formula and the 3T method on the three representative WtE plants and two biomass gasification plants of Table 1.

vastly different characteristics may project similar R1 "behavior". At the same time, R1 returns relatively high values for the two gasification plants, i.e. 1.056 for plant D and 1.046 for plant E and this shows that the electrical efficiency is overshadowed by the high thermal efficiency. This outcome is contrary to the intention of the R1 formula, which had the scope to promote the production of electricity. Thus, the R1 formula does not serve the purpose that it initially intended to serve. In all fairness, there are two pints to be made on this aspect. On the one hand, the two methods have different range of expected values and switching to the 3T Method could cause (for the moment) major confusion. On the other hand, the solely electricity production plants are primarily located in southern climates with less heat demand and this aspect has been "corrected" with the integration of the climate correction factor.

3.2. Assessment of the climate correction factor

Fig. 3 presents the heating degree-days and the climate correction factor for representative European cities. A dashed line in the figure represents the limit of 2150 heating degree days below which the climate correction factor is set to 1.25 which the maximum possible value. Overall, a general assessment is that for the present status this correction factor is compatible with the EU case. The ranges that are set by the legislators are representative and relevant. A minor critical assessment of the results highlights two negative aspects. Firstly, all the southern/Mediterranean countries are grouped together and no differentiation is possible. Secondly, the heating degree-days per year are continuously dropping in Europe [24]. Thus, it is not outside the realm of possibility that cities like London or Paris -which are close to the limit of 2150 HDD-, will be clustered together with southern cities like Lisbon or Athens.

Fig. 4 shows a similar analysis of the heating degree-days and the calculation of the climate correction factor for representative U.S. cities. The analysis shows that the use of the same climate equations that apply well for Europe are as well for the case of United States. The analysis shows that Miami, Los Angeles, San Francesco and Atlanta would be all under the limit and would receive the maximum bonus from the climate correction factor equal to 1.25. Of course, this is only a theoretical argument since the R1 is not applied in United States. However, the point is that the application of the climate correction factor has not a universal compatibility.

3.3. Comparison of numerical ranges for the 3T method and the R1 formula

Fig. 5 shows the returned R1 values for a wide range of electric and heat efficiencies. A point to be made about the nature of the R1 formula is that heat plays a significant role in the calculation of the R1 value, although this was not the intention of the lawmakers. Reimann (2012), presented the R1 status report for all the European WtE plants for the period 2007–2010 and his results showed that the solely heat producing plants had an average R1 value of 0.64 and the solely electricity plants had an average R1 value of 0.55 which set them below the acceptable limit [25].

Fig. 6 presents different calculated ranges of the 3T method that take into consideration different levels of metal recovery and electric efficiency of 15%. Three characteristic curves represent metal recovery levels of 40%, 50% and 70%. For all these cases, the equivalent R1 value-curve is a single line as shown in Fig. 5. These results start to make the case for the 3T Method and the integration of extra additional parameters. The assessment of the recovery of metal is an important aspect as has been mentioned by several published studies, e.g. Ref.

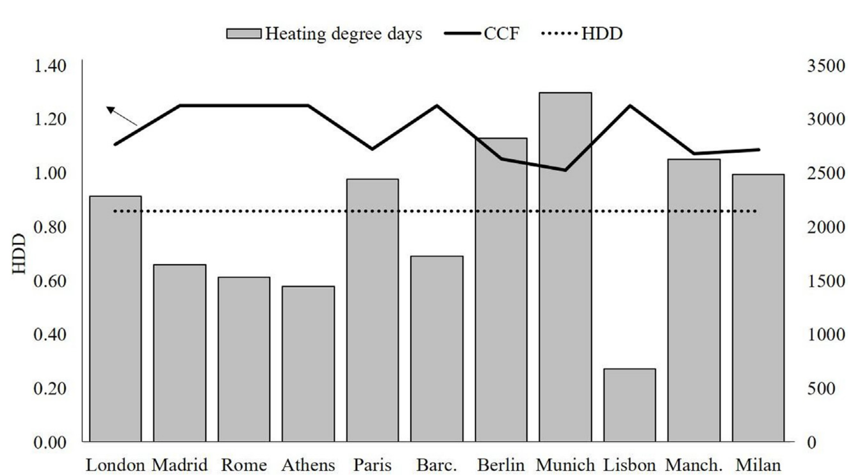

Fig. 3. Heating Degree Days and the Climate Correction Factor for representative European cities.

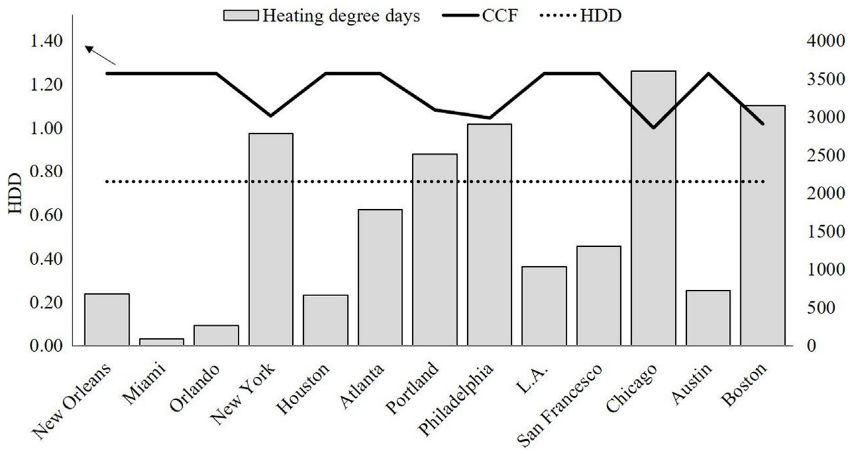

Fig. 4. Heating Degree Days and the Climate Correction Factor for representative U.S. cities.

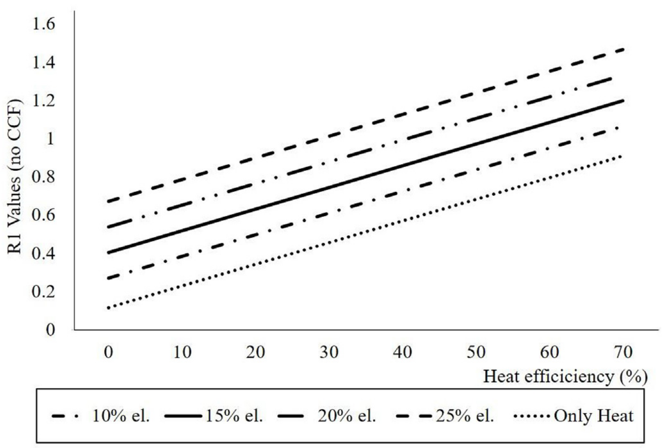

Fig. 5. R1 values for a wide range of heat and electrical efficiencies.

[26].

Another parameter that the 3T method takes into consideration is the quality of the produced steam, which may vary significantly according to the temperatures and pressure. Fig. 7, presents the 3T values and the R1 values for CHP production of 60% but for different CHP combinations. Just for reference, the metal recovery exergetic efficiency is set to 50%. The results, present different 3T values for different steam temperatures (and atmospheric pressures) for the sam levels of electricity production. As shown in the Figure, this is not the case for the application of the R1 formula. Thus, the 3T method is able to evaluate the steam quality, which may have different industrial applications as presented in recent publications [27].

3.4. Discussion of results and critical points

An attribute of the 3T method that was highlighted in this study was the ability of the method to account for produced materials from thermal processes, like gasification and pyrolysis, which produce char and biooil [28]. MSW gasification is not a commonly applied practice at the moment, but some examples can be found in the literature [29]. Specifically, the authors analyzed the syngas quality of a commercial scale MSW gasifier. A point to be made is that the 3T method is able to evaluate technologies that produce only fuels/materials and CHP production is not necessary like for the case the R1. A possible future challenge would be the expansion of the 3T method for non-thermal biofuel production technologies from MSW like the case of bioethanol via Simultaneous Saccharification and Fermentation (SSF) [30]. An interesting recenet application has been the use of the 3T method for the assessment of Landfill Mining (plus Landfill Gas) [31] and it would be interesting to investigate the further the potential of the method on industrial processes that focus solely on metal separation and recovery [32]. Finally, the R1 formula showed high sensitivity to the thermal efficiency and future work that would focus on the case of WtE for district heating [33] would be interesting.

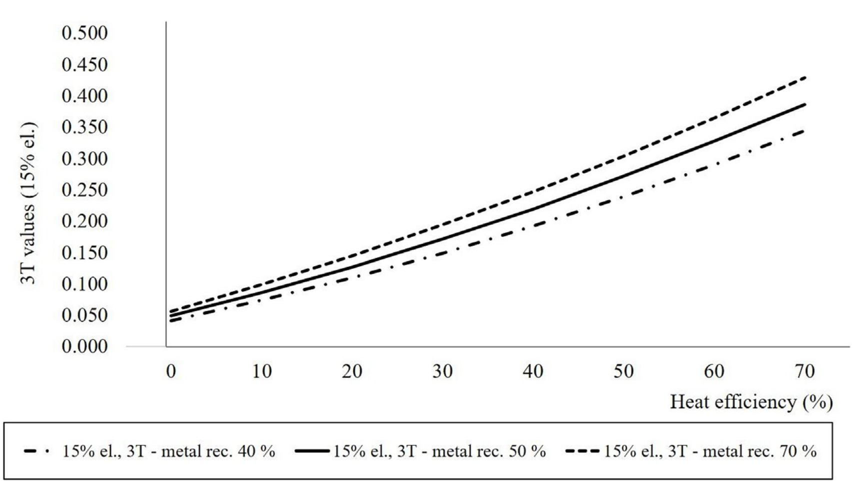

Fig. 6. 3T values for different metal recovery efficiencies and for fixed 15% electrical efficiency.

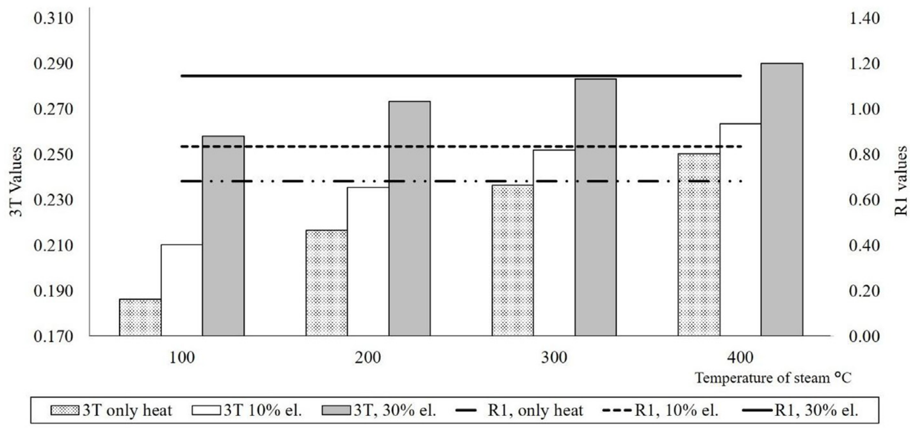

Fig. 7. R1 and 3T values for a wide range of electrical efficiencies and for different steam temperatures.

4. Conclusions

This study had the scope to compare the numerical results from the application of the R1 formula and the 3T method for the case of three incineration plants and two gasification plants. The comparison between the two technologies is unique and is the main novelty of the study. The two methodologies have different range of potential returned values with the R1 having usually values between 0.5 and 1, and the 3T Method ranging between 0.2 and 0.3. Independently from that, the two methods showed to have different tendencies in the way that they were fluctuating according to the change of the input parameters. On the one hand, this can be attributed on the different way that the two methods account for the produced heat. On the other hand, the 3T method considers as well also the quality of the materials, e.g. metals. In respect to the climate correction factor, the analysis showed a good fit with the present status quo of Europe but not with the case of United States. Also, the heating degree-days are reducing steadily every year and maybe a post-correction will be necessary to the existing correction factor. Finally, the 3T Method has multiple layers of analysis and is able to provide more information in respect to the R1 formula. Characteristically, the 3T Method is able to account for the quality of the produced heat by taking into consideration the exergy of the produced steam.

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